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PERFORATING ABILITY OF ARROW-TYPE PROJECTILES:
EFFECT OF PROJECTILE LENGTH (U)

by

C. W. CURTIS   O. R. KYMER   H. E. FITZINGER

February 1958

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REPORT No. R-1436

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PERFORATING ABILITY OF ARROW-TYPE PROJECTILES:
EFFECT OF PROJECTILE LENGTH (U)

February 1958

OCO Project No. TA1-5002
DA Project No. 5A04-01-001

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OBJECT

To investigate the effect of projectile length on the perforating ability of arrow-type projectiles.

SUMMARY

Tests have been carried out to determine the effect of projectile length on the perforating ability of small caliber arrow-type projectiles fired against rolled homogeneous armor at 60° obliquity. The tests included projectiles from 3.0 to 16.7 calibers long and targets from 1.11 to 4.75 calibers thick. The projectiles were made of hardened steel and had diameters of 0.263 in. to 0.450 in.

At this large angle of attack and for projectiles of a given diameter, the energy required for perforation increases with increase in projectile length for all plate thicknesses tested.

An equation has been developed which relates projectile length, as well as the usual projectile and plate parameters, to the energy required to defeat a target. Although this equation is empirical, it predicts to a reasonable accuracy the observed effects due to changes in the various parameters and should, therefore, be useful for purposes of projectile design. With the adjustment of certain constants from limited firing data, the equation should be applicable to large as well as small caliber arrow-type projectiles.

AUTHORIZATION

Ltr, Picatinny Arsenal, ORDBB-TE3, 471.14/G-281, 26 July 1955

INTRODUCTION

With the development of fin stabilization it has become possible to fire very long projectiles with the consequent benefits of high caliber density. Two of these benefits are: less retardation in flight and a greater concentration of energy into a small area of the target plate. Also, compared to spin-stabilized subcaliber projectiles, a greater ratio of core to carrier weight can be obtained. The result has been the development of effective arrow-type projectiles.

For a fin-stabilized arrow-type projectile, there is no effective limit to the length set by the exterior ballistic performance. On the other hand, the length would be limited by the terminal ballistic performance if there were serious deterioration as the length increased. Thus a correlation between projectile length and perforating ability becomes an important factor. Previously, no notable correlation between these quantities had been established, probably because so little variation in length is possible with a spin-stabilized projectile. Long projectiles cannot be stabilized by spinning. This correlation and the possible deterioration of terminal ballistic performance with length are the subject of the present report.

Only firings at 60° obliquity are considered.

PROJECTILE DIMENSIONS AND CONDITIONS OF IMPACT

The variables investigated, together with their respective symbols, follow.

l - Projectile length - 1.35 in. to 5 in.
d - Projectile diameter - 0.263 in. to 0.450 in.
l/d - Projectile length to diameter ratio - 3.0 to 16.7
t - Plate thickness - 1/2 in. to 1 1/4 in.
t/d - Thickness to diameter ratio - 1.11 to 4.75
Angle of attack - 60° (90/40 mm results - 55° and 60°)

A description of the various experimental projectiles, together with their launching and flight characteristics, is included in the Appendix.

RESULTS

Terminal Ballistic Data

A summary of the ballistic results is given in Table I. This Table includes the various parameters listed above, together with the protection ballistic limits (PBL's) and specific limit energies (SLE's). A discussion and correlation of the results are contained in the following two sections. All plates were rolled homogeneous armor of 280-320 Bhn.

Effect of Projectile Length

Firing results for three ℓ/d ratio groups are shown in Figure 1, where the logarithm of the SLE is plotted against the logarithm of the caliber plate thickness (t/d). It can be seen in Figure 1 that the SLE for constant t/d, required to defeat the target, is inversely proportional to the projectile length. Hence, the shorter projectiles are more efficient penetrators than the longer ones. The curves for a given ℓ/d ratio are not parallel, but seem to have less separation at larger t/d's. Because the plot is logarithmic, this means that the fractional increase in SLE due to a given increase in projectile length becomes less as the t/d ratio becomes greater. Also, since the plots are not straight lines, the SLE is not directly proportional to a power of t/d.

Derivation of Perforation Formula

No simple perforation formula has been found which represents these data correctly in all details. However, the following equation takes into account the main variations.

$$ SLE = \frac{WV_L^2}{d^3} = \frac{W^*V_L^2}{d^3}\left[1 + c\left(\frac{\ell}{t}\right)^n\right] = a\left[\frac{t}{d} - b\right]\left[1 + c\left(\frac{\ell}{t}\right)^n\right] \tag{1} $$

All the variables of this equation are defined in the notes of Table I except W^* and the constants: a, b, c, and n. W^* is defined by

$$ W^* = \frac{W}{1 + c\left(\frac{\ell}{t}\right)^n} $$

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Table I. Summary of Arrow-type Projectile Data

d - Projectile diameter (in.)
l - Projectile length (in.)
W - Projectile weight (lb)
t - Plate thickness (in.)
V_L - Protection ballistic limit* of plate (f/s)
SLE - Specific limit energy** = WV_L^2/d^3 (lb ft^2/in.^{3} sec^2 × 10^6)

Projectile No.	Figure Symbol***	d	l/d	W/d	Plate Thickness (in.)	t/d	l/t	V_L	SLE
36	□	0.450	3.0	0.556					
					1/2	1.11	2.70	3630	7.3
					3/4	1.67	1.80	5950	19.7
37	x	0.375	4.9	0.962					
					1/2	1.33	3.60	3710	13.3
					3/4	2.00	2.45	5250	26.6
19	+	0.312	6.4	1.222					
					1/2	1.60	4.00	4150	21.3
					3/4	2.40	2.67	5700	39.6
					1	3.20	2.00	6300	48.4
38	○	0.300	9.0	1.878					
					1/2	1.67	5.39	3550	23.6
					3/4	2.50	3.60	4530	38.5
					1	3.33	2.70	5575	58.2
16	⊗	0.312	9.6	1.952					
					1/2	1.60	6.00	3335	21.7
					3/4	2.40	3.40	4300	36.2
					1	3.20	3.00	5635	62.0
					1 1/8	3.60	2.67	5570	60.7
33	⊕	0.300	10.0	2.033					
					3/4	2.50	4.00	4350	38.4
					1	3.33	3.00	5150	54.0
					1 1/4	4.17	2.40	5780	67.9
14	△	0.312	12.8	2.654					
					1	3.20	4.00	4860	62.6
39	▲(x)	0.263	13.2	2.786					
					1/2	1.9	6.94	3500	34.2
					3/4	2.85	4.63	4600	59.2
					1	3.80	3.47	5150	74.0
					1 1/4	4.75	2.78	5400	62.4
34	▲(+)	0.300	13.3	2.763					
					3/4	2.50	5.32	4200	48.8
					1 1/4	4.17	3.20	5275	77.0
15	▽	0.312	16.0	3.305					
					3/4	2.40	6.66	4025	54.9
					1	3.20	5.00	4400	65.6
35	▽(x)	0.300	16.7	3.478					
					1/2	1.67	10.0	3150	34.5
					1 1/4	4.17	4.00	4650	75.2

*A protection-complete penetration is obtained whenever a fragment or fragments of either the impacting projectile or the plate are ejected from the rear of the plate with sufficient energy to perforate a thin, mild steel plate (about 0.020 in.) or equivalent screen placed parallel to and approximately six inches rearward of the plate.

**The specific limit energy is the kinetic energy of the projectile divided by the cube of its diameter.

***These symbols are used in Figures 1 through 4.

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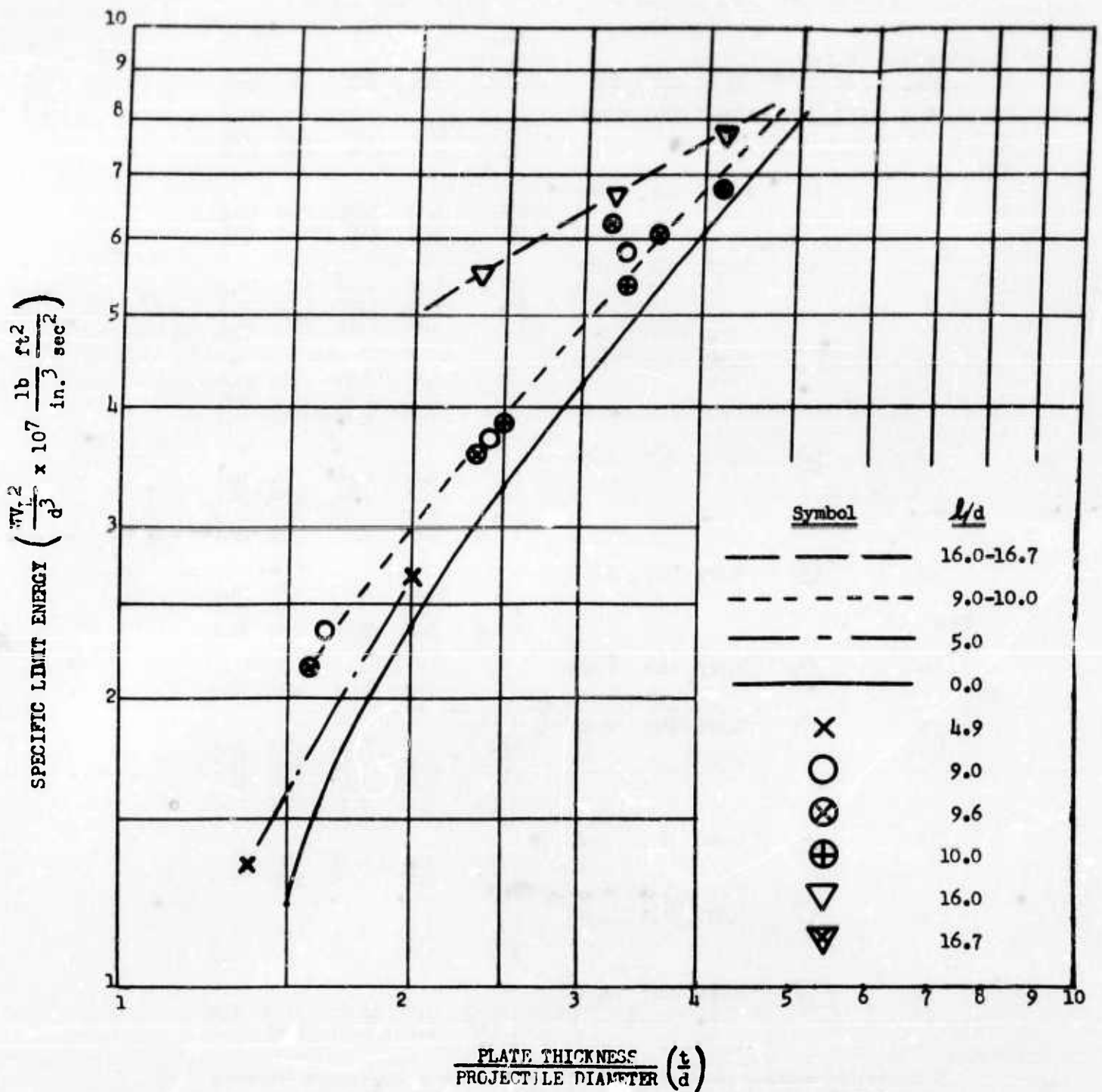Figure 1. Effect of projectile length on penetrating ability
of arrow-type monobloc steel projectiles vs RH armor at
60° obliquity

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and may be considered as that fraction of the projectile mass which is effective in perforating the plate. The constants a, b, c, and n are determined from the ballistic data.

It will be noted that this equation leads to the same types of variation for the perforation limits as described in the last section. Thus, with $\ell = 0$, WV_L^2/d^3 vs t/d on a log-log plot would be a curved line with a slope approaching unity for large t/d. Also, the effect of increasing ℓ is to increase SLE above the value given by $a[t/d-b]$, but this effect becomes less with increasing t.

Figure 2 shows all perforation data, together with curves derived from equation (1) with $a = 1.86 \times 10^7$, b = 0.73, c = 0.015, and n = 2. The values for a and b were determined from the solid lines drawn in Figures 1 and 2 as an estimate of the penetration curve for $\ell = 0$.

Equation (1) may be rewritten as

$$\frac{\dfrac{WV_L^2}{d^3} - \dfrac{W^*V_L^2}{d^3}}{\dfrac{W^*V_L^2}{d^3}} = c\left(\frac{\ell}{t}\right)^n \qquad (2)$$

Therefore c and n can, in principle, be determined from a plot on log-log paper of the left hand side of equation (2) vs ℓ/t. Such a plot is shown in Figure 3. If equation (1) were exactly true, if the values for a and b were correct, and if there were no scatter in the data, a plot of the data would result in a straight line. From this graph, c and n were given values of 0.015 and 2, respectively.

Figure 4, which is a plot of the SLE's adjusted to $\ell = 0$, shows how much the spread in data has been reduced. In this figure the SLE, WV_L^2/d^3, is adjusted by dividing by $(\ell + 0.015 [\ell/t]^2)$, which is the length-dependent term in equation (1). However, it may be noted that the adjusted values are still too high in the range for t/d = 3 to 4. Furthermore, it does not account for the curvature of the plots in Figures 1 and 2.

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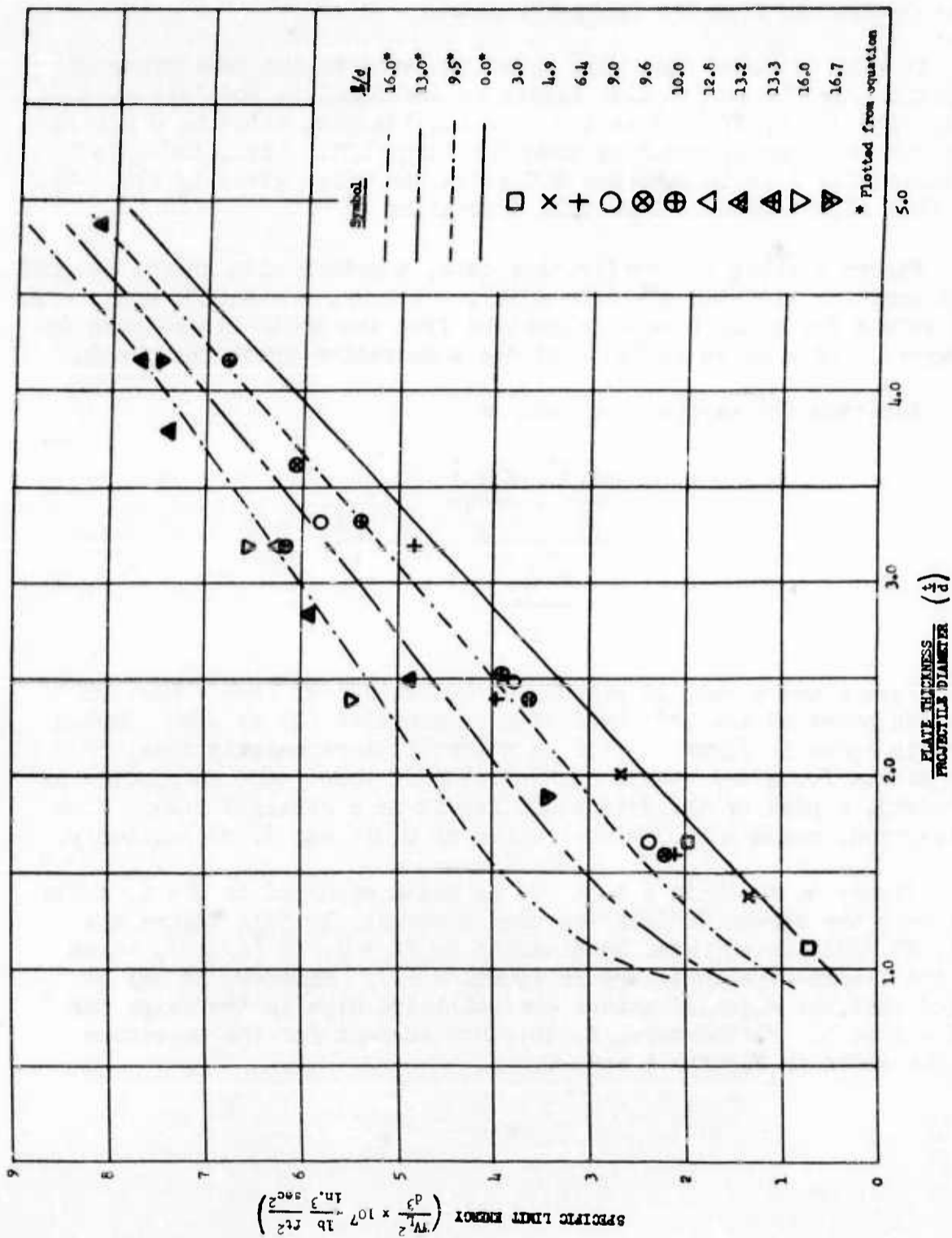Figure 2. Perforation energy vs plate thickness for arrow-type monobloc steel projectiles of various lengths at 60° obliquity
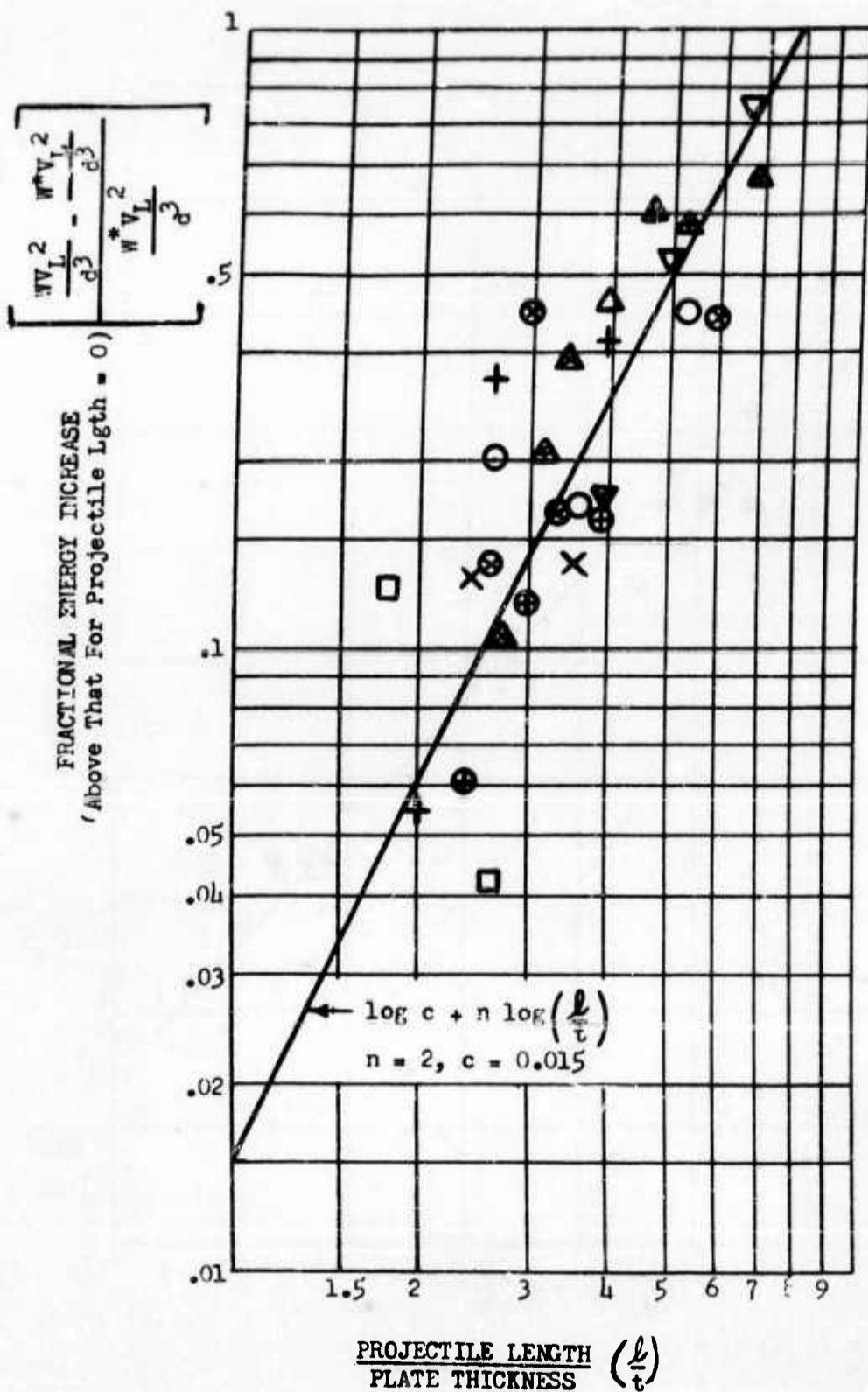
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Figure 3. Correction for perforation energy due to
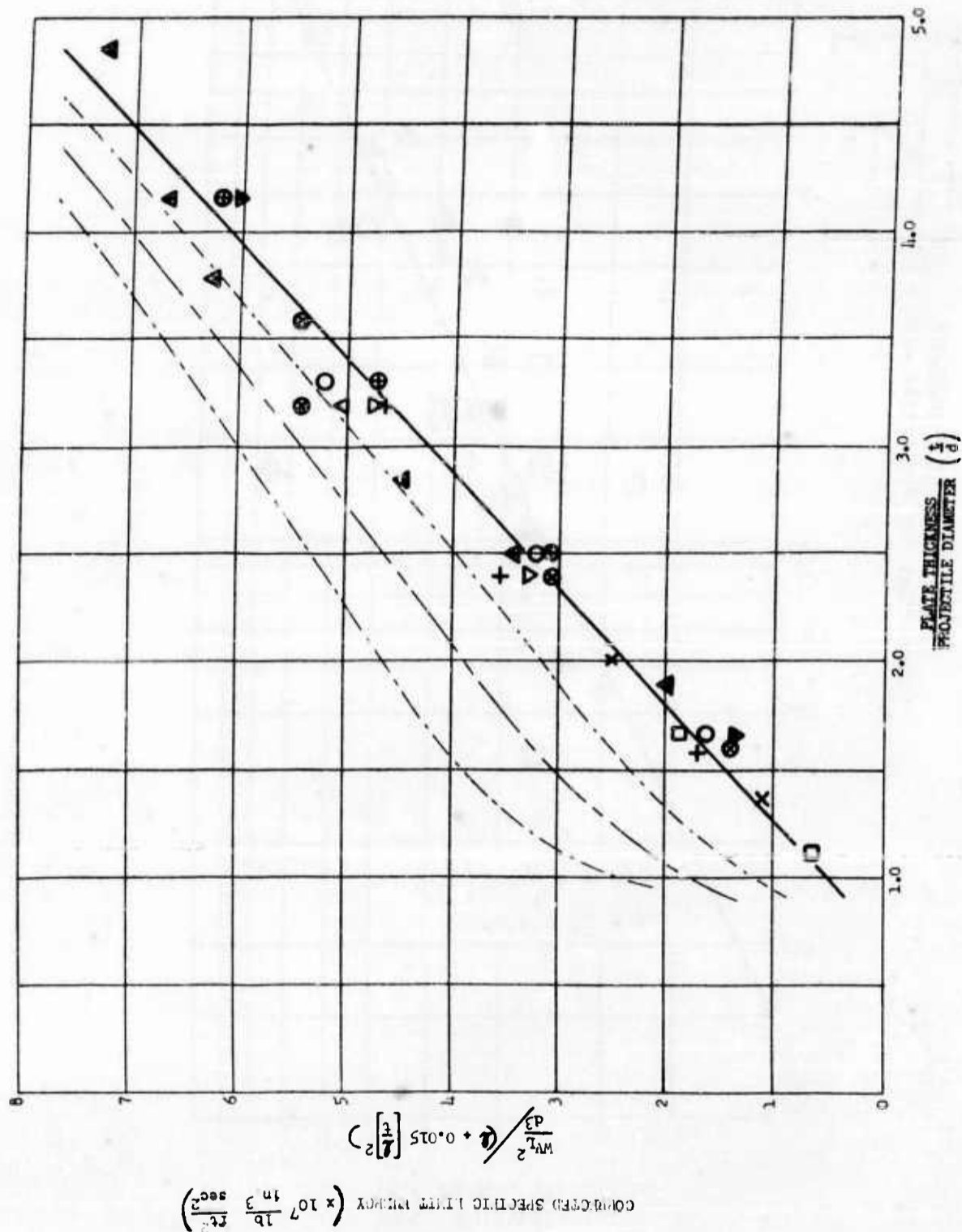projectile length

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Figure 4. Perforation energy, corrected for projectile length,
vs plate thickness for arrow-type monobloc steel projectiles
at 60° obliquity

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Perforation Formula for Full Caliber Projectiles

Very few perforation data are available for comparison between large and small scale solid steel arrow results at 60° obliquity. Considerably more penetration data are available for the 90/40 mm APT82 arrow projectile at 55° obliquity. These data are plotted in Figure 5, together with a few results for 60° angle of attack.

A 90/40 mm APT82 projectile, 8.57 calibers long, fired at 60° obliquity vs plate 2.6 calibers thick, had a specific limit energy of 3.3×10^7 while for the same angles of attack against plate 3.8 calibers thick, the SLE was 4.7×10^7. Each of these values is about 20 per cent less than that predicted by the perforation formula based on the small caliber data. This is not unreasonable in view of the large difference in size.

In order to correlate the full caliber, 55° data by use of equation (1), it is to be expected that the values for some of the constants would be different than for the small caliber arrows, both because of a scale effect and a different angle of attack. As a result, the values for the constants a and b were changed to 1.4×10^7 and 0.8, respectively. Therefore,

$$SLE = 1.4 \times 10^7 \left[t/d - 0.80 \right] \left[1 + 0.015 \left(\ell/t \right)^2 \right]$$

It may be noted in Figure 5 that the curves plotted with this equation fall fairly close to the plotted ballistic data and, particularly, that the observed changes are in the expected directions.

CONCLUSIONS

1. For arrow-type projectiles of a given diameter, the energy required for defeating RH armor at 60° obliquity increases as the projectile length increases.

2. An equation has been developed which relates projectile length, as well as the usual projectile and plate parameters, to the energy required to defeat a target. With the adjustment of certain constants from limited firing data, the equation should be applicable to large as well as small caliber arrow-type projectiles. Also, it should reduce considerably the amount of ballistic testing.

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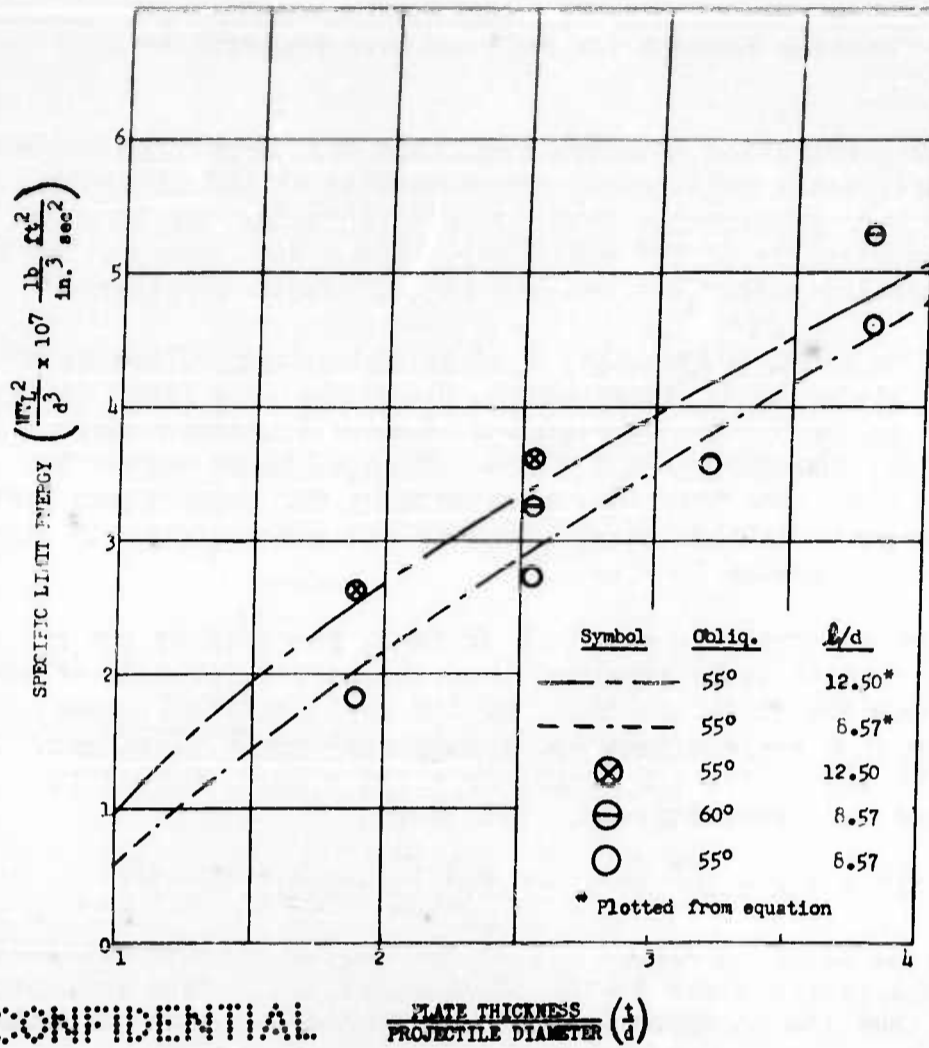
Figure 5. Perforation energy vs plate thickness for 40 mm
(T82E16, E22, E23) arrow-type monobloc steel projectiles
vs RH armor at 55° and 60° obliquity

WORK IN PROGRESS

Penetration studies are being continued with Models 36, 37,
38, and 39, which have different lengths and diameters but the
same weight, against a wide variety of plate thicknesses and ob-
liquities ranging from 0° to 70°. The results of this work will
be reported at a future date.

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APPENDIX

PROJECTILE DESIGN

Penetrators

Sketches for all penetrator designs are included in Figures 6 and 7. Projectile lengths and weights are contained in Table II, which also includes weights and dimensions for launching accessories, such as carriers, stabilizers, obturators, and steel disc pushers. For ease of machining, the first projectiles (Models 14, 15, 16, 19, 33, 34, and 35 - Figure 6) had 45° included angle, conical noses. The latest four designs (Models 36 to 39 - Figure 7) had ogival noses of 1 1/2 caliber radius, similar to most conventional AP shot. There is no reason to believe that any difference in penetration performance exists between the two shapes, since all projectiles shattered at the obliquities and velocities investigated in this report.

All projectiles were machined from drill rod (1095 steel), and heat treated to Rc 62 to 65 hardness.

Stabilizers

Due to the short range (25 to 30 ft) over which the arrow projectiles were fired, they were drag-stabilized by means of disc-like aluminum alloy bases (Figure 8). Over this short range the lesser retardation afforded by fins was considered insufficient to compensate for the greater cost of machining; in addition, the range was too short for the projectile yaw to be damped out (if there is yaw) with either type of stabilizer. Penetration data obtained with projectiles having yaw (determined by means of shadowphotography and radiography) were excluded from this report.

The first base design, shown in Figure 8A, was not very successful. Shadowgraphs, which were taken of each projectile in flight, indicated that turbulence and, hence, the trailing shock wave, started far forward on the body (Figure 9). Two methods were tried to overcome this condition; the first was to attach fins (as shown in Figure 8B), the second was to taper the base (as shown in Figure 8C). Both designs showed some stability improvement; however, there was not much difference between the two. The use of fins was discontinued since they are more difficult and expensive to make.

There were indications of a tendency for the aluminum alloy base behind the arrow to plug on setback. To avoid this, a hole was drilled completely through the base and a hardened (Rc 45) steel disc was placed behind the projectile as a "pusher." This design is the one presently used in testing Models 38 and 39.
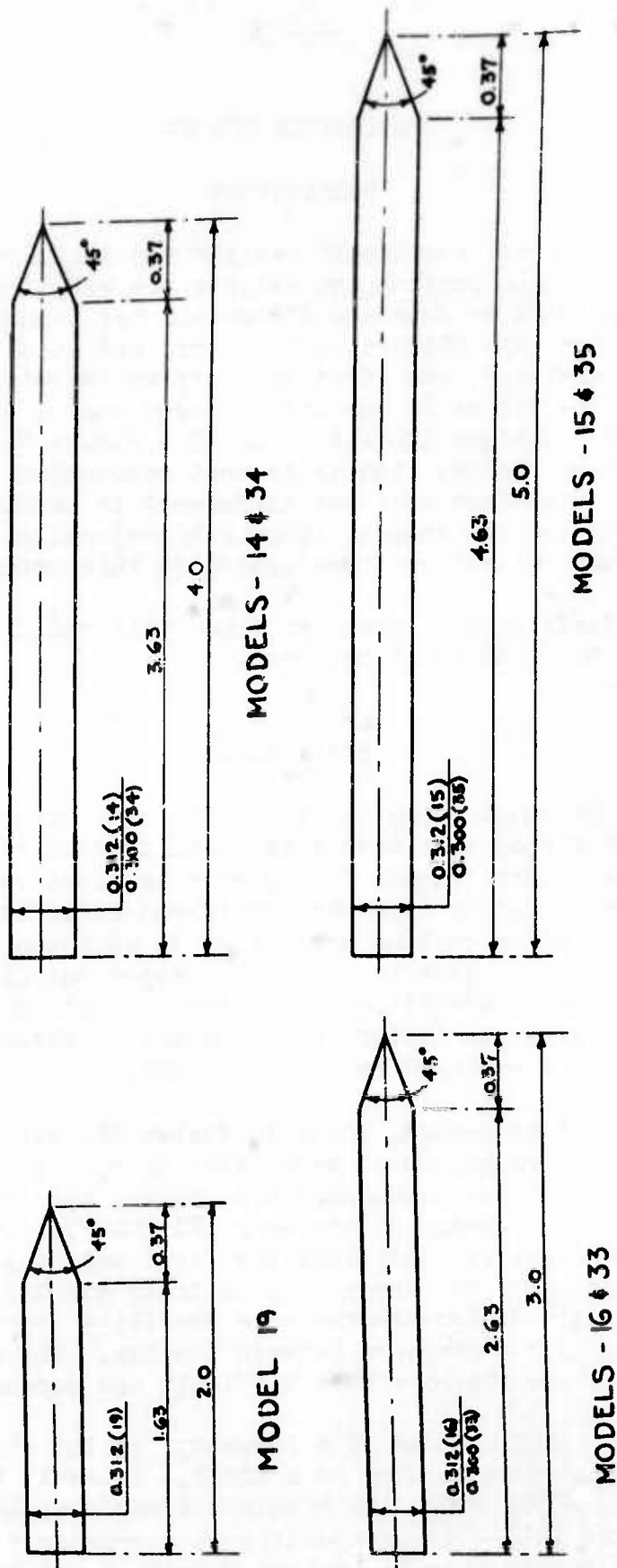
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Figure 6. Penetrator designs for arrow-type projectiles
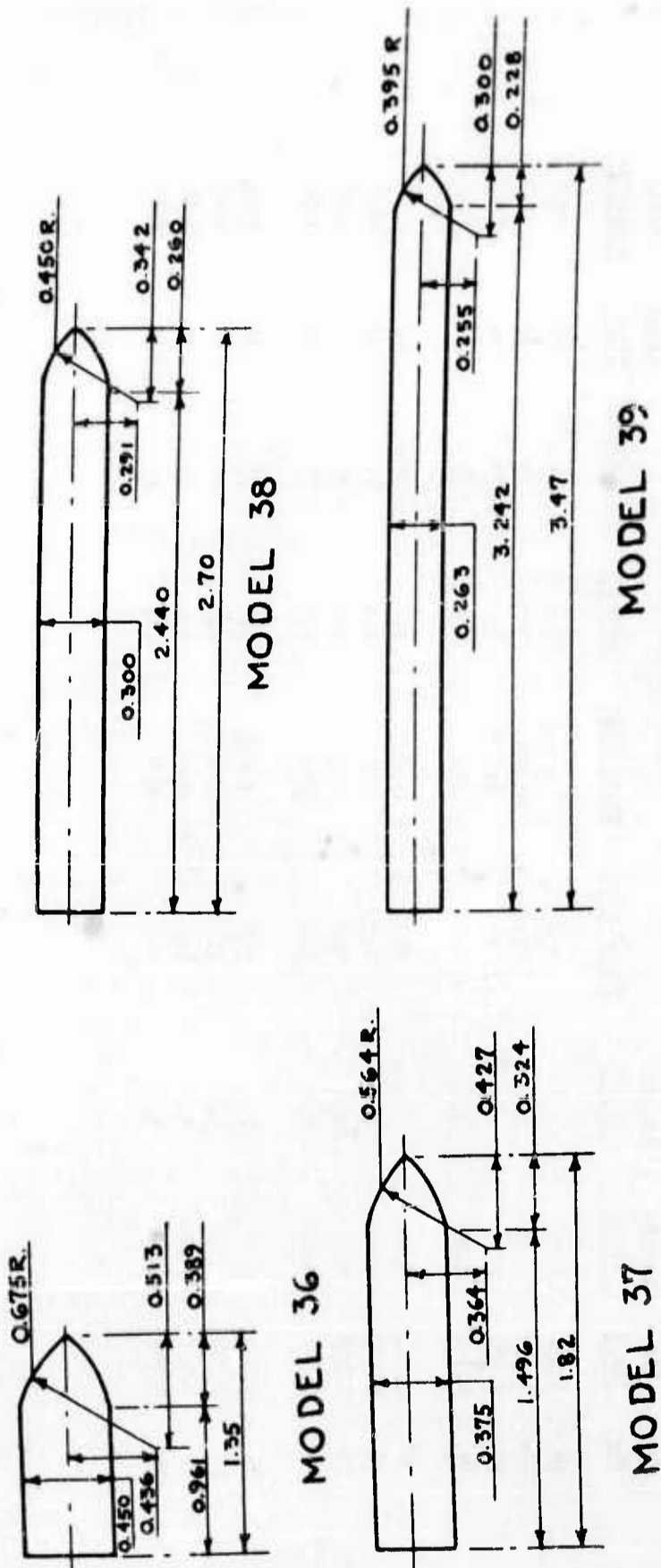
MODELS - 14 & 34

MODELS - 15 & 35

MODEL 19

MODELS - 16 & 33

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Figure 7. Penetrator designs for arrow-type projectiles

Table II. Projectile and Launching Accessory Characteristics

No.	Projectile Dia (in.)	Length (in.)	Carrier Length (in.)	Weight (gr) Penetrator	Stabilizer	Carrier	Obturators	Steel Disc	Total Propelled
96	0.450	1.35	1.0	355	-	220	45	130	750
37A	0.375	1.82	1.0	355	187	333	45	133	1050
37	0.375	1.82	1.0	355	211	333	79	214	1192
19	0.312	2.00	1.5	260	298	330	79	214	1181
98	0.300	2.70	2.0	355	155	421	79	214	1224
16	0.312	3.00	2.0	413	298	494	79	214	1498
33	0.300	3.00	2.0	384	171	330	79	214	1298
14	0.312	4.00	3.0	564	298	707	79	214	1852
99	0.263	3.47	2.4	355	164	517	79	214	1329
34	0.300	4.00	3.0	522	171	600	79	214	1586
15	0.312	5.00	3.0	715	298	330	79	214	2296
35	0.301	5.00	3.0	657	171	600	79	214	1721

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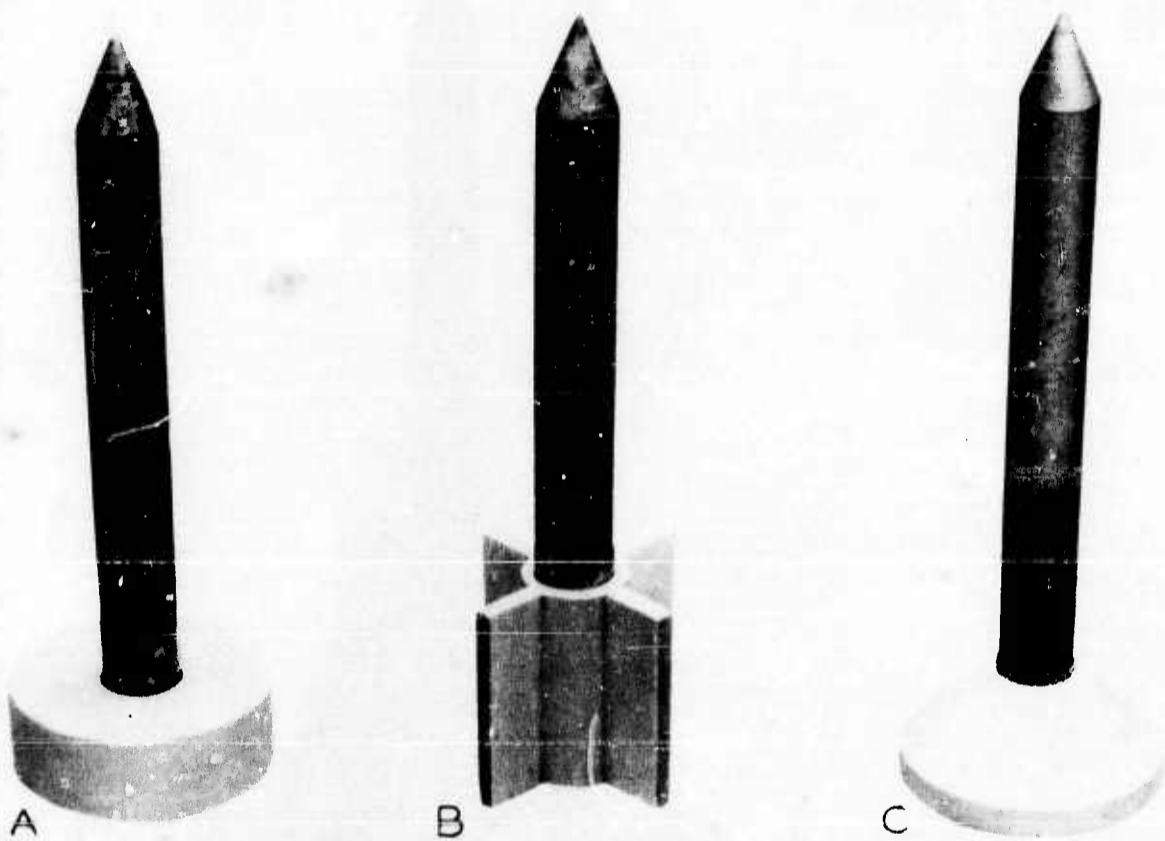

Figure 8. Stabilizer (aluminum alloy) designs for
arrow-type projectiles

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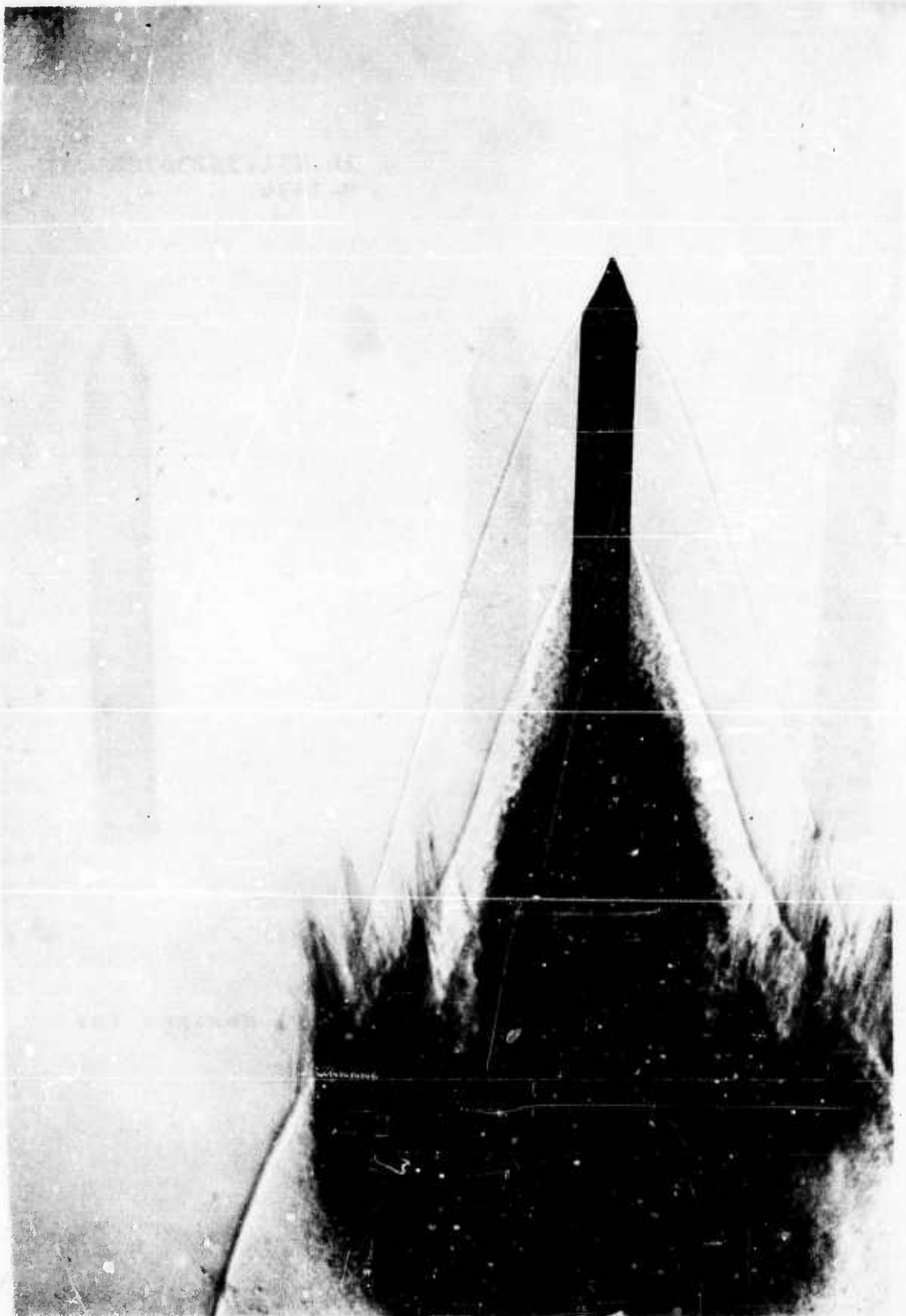Figure 9. Shadowgraph of model 14 projectile fired at 4900 fps, showing turbulence

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Since drag stabilization of short projectiles ($\ell/d \leq 5$) was not accomplished, they were fired from a 20 mm rifled gun. Model 37 projectiles with $\ell/d = 4.9$ could not be stabilized by either spinning or dragging, so the possibility of combining the two types of stabilization was investigated. The first base design for this projectile, similar to the aluminum alloy design in Figure 8A, was made of steel. Since the weight of the base of this design was more than that of the penetrator, the modification (similar to Figure 8C), as shown in Figure 10, was made and is now in use for Model 37 projectiles.

Sabots

In firing Models 36 and 37 from rifled guns, two types of plastic (A and B)* were tried. Plastic A did not have sufficient strength; therefore two designs (Figure 11) of Plastic B were tried. Design 1 could possibly have been used for low velocity firing of Model 36 projectiles, but the plastic broke in the gun at higher velocities and pressures; design 2 was therefore adopted. Model 37 projectiles fired with design 1 sabots were not stable due to launching and exterior ballistic deficiencies; therefore design 2 was used for this model.

For all models fired from a smooth bore gun, Plastic A has proven adequate. The first design used is shown in Figure 12A. The longitudinal slots were machined to assist the sabots in discarding. The later sabots (Figure 12B) were made of four segments for ease in machining and facility in discarding.

Neoprene discs, 1/4 inch thick, were used as obturators behind all projectiles.

LAUNCHING DEVICES

Guns

Projectiles, Models 36 and 37, were fired from 20 mm, standard twist, rifled guns. The barrel travel length varied from 52 to 138 inches; one Mann-type barrel or two joined together were used to obtain the desired velocities. The barrel at the breech end was machined to permit insertion of the round, but was not chambered.

*See Code Sheet

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Figure 10. Stabilizer (steel) design for arrow-type projectile
(Model 37)

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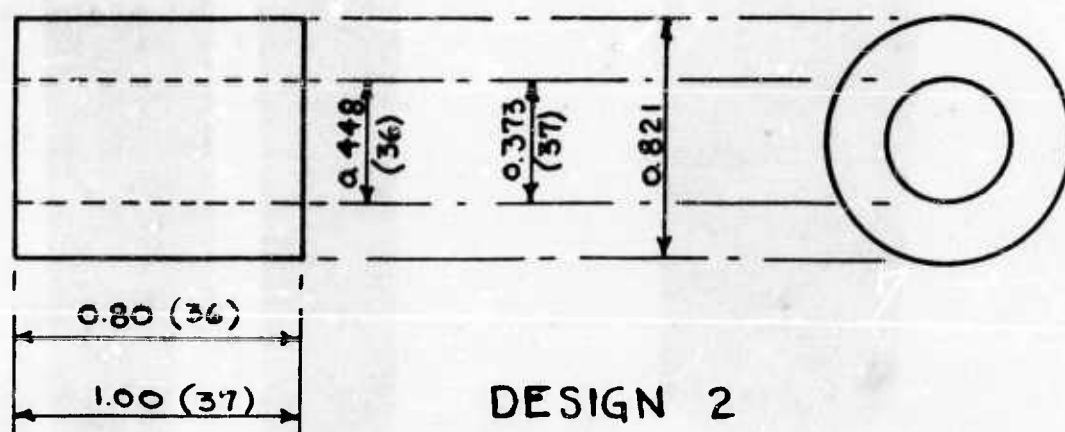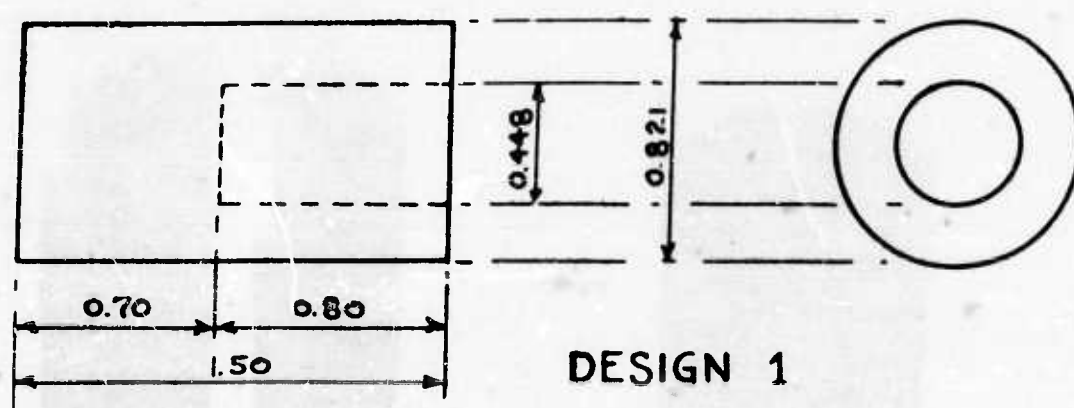
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Figure 11. Sabot designs (plastic) for arrow-type projectiles

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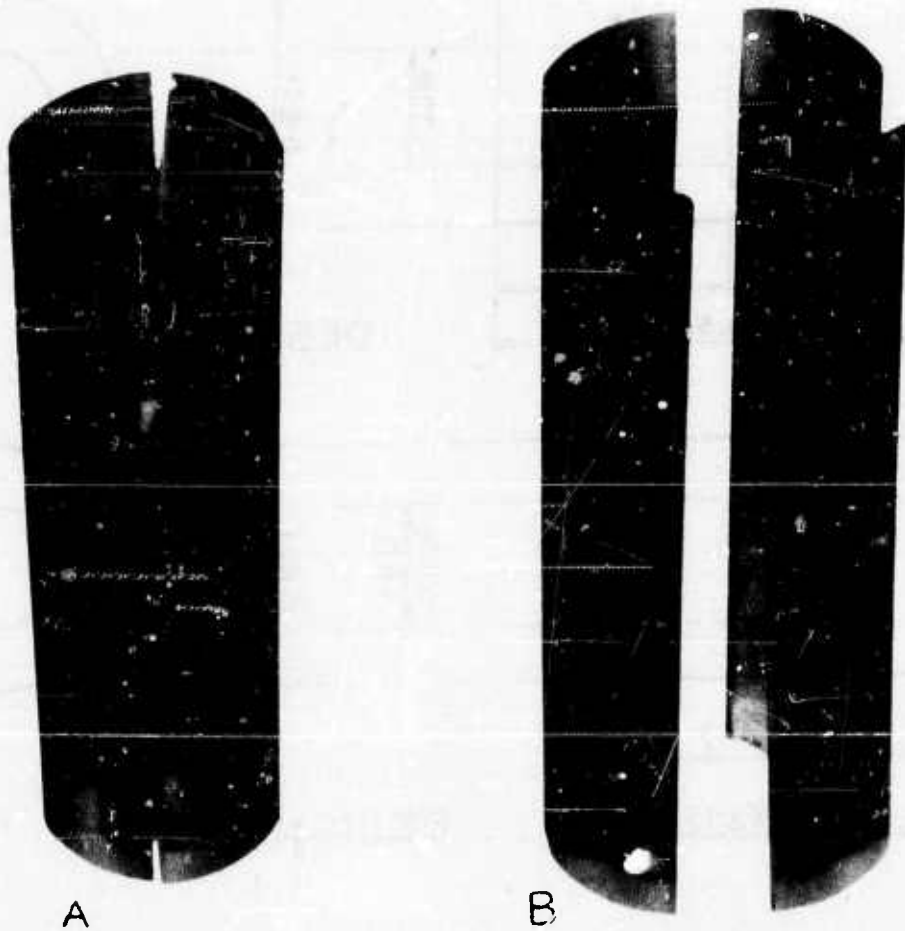R-1436

Figure 12. Sabot designs (plastic) for arrow-type projectiles

All other projectiles were fired from 27 mm blank (unrifled)
barrels. The travel length in these tubes ranged from 60 to 154
inches. Either single or double length Mann-type barrels were used.
In addition, one of the double length barrels was adapted for
vacuum firing. A barrel pressure of less than one millimeter of
mercury was achieved prior to firing.

Chambers

Depending upon the velocity desired, one of three chambers was
used. For relatively low velocities (1800 to 3600 fps), an un-
necked caliber .60 cartridge case was used in a modified convention-
al size chamber.

For higher velocities (3200 to 5500 fps), the chamber shown
in Figure 13 was used. This chamber has two pressure stations which
permit the taking of simultaneous pressure measurements. With this
chamber, no cartridge case was used with the exception of a one-inch
base section cut from a caliber .60 case. The base section was used
to hold the primer and perforated flash tube. With only a primer,
a large pressure differential was observed between the front and
rear pressure stations. To equalize these pressures, different
methods were tried, including front ignition, central ignition,
empty perforated flash tubes, and flash tubes partially filled with
black powder. The empty perforated flash tube gave the best results.
If a combination of powders was required, it was found that the
placing of the slower powder near the primer and the faster powder
near the projectile was more satisfactory than blending the powders.

For hyper velocities (4400 to 7000 fps), the chamber shown in
Figure 14 was used. A one-inch section of a caliber .60 cartridge
case was used, similar to the one used for the chamber of Figure
13. Although the projectile velocities obtained with this chamber
overlap those obtained with the previous one, the pressures are
much lower for similar velocities. The flash tube system proved
to be unnecessary for this chamber. However, it was found that
FFFG black powder adjacent to the primer was needed for proper
ignition.

In all cases M52A4 electric primers were used.

Inasmuch as none of the projectiles were crimped into the case,
it was found that more consistent ignition and more reproducible
velocities could be obtained by placing a thin brass disc between
the chamber and the gun tube.

Copper crusher gages were used for all rounds, except for a
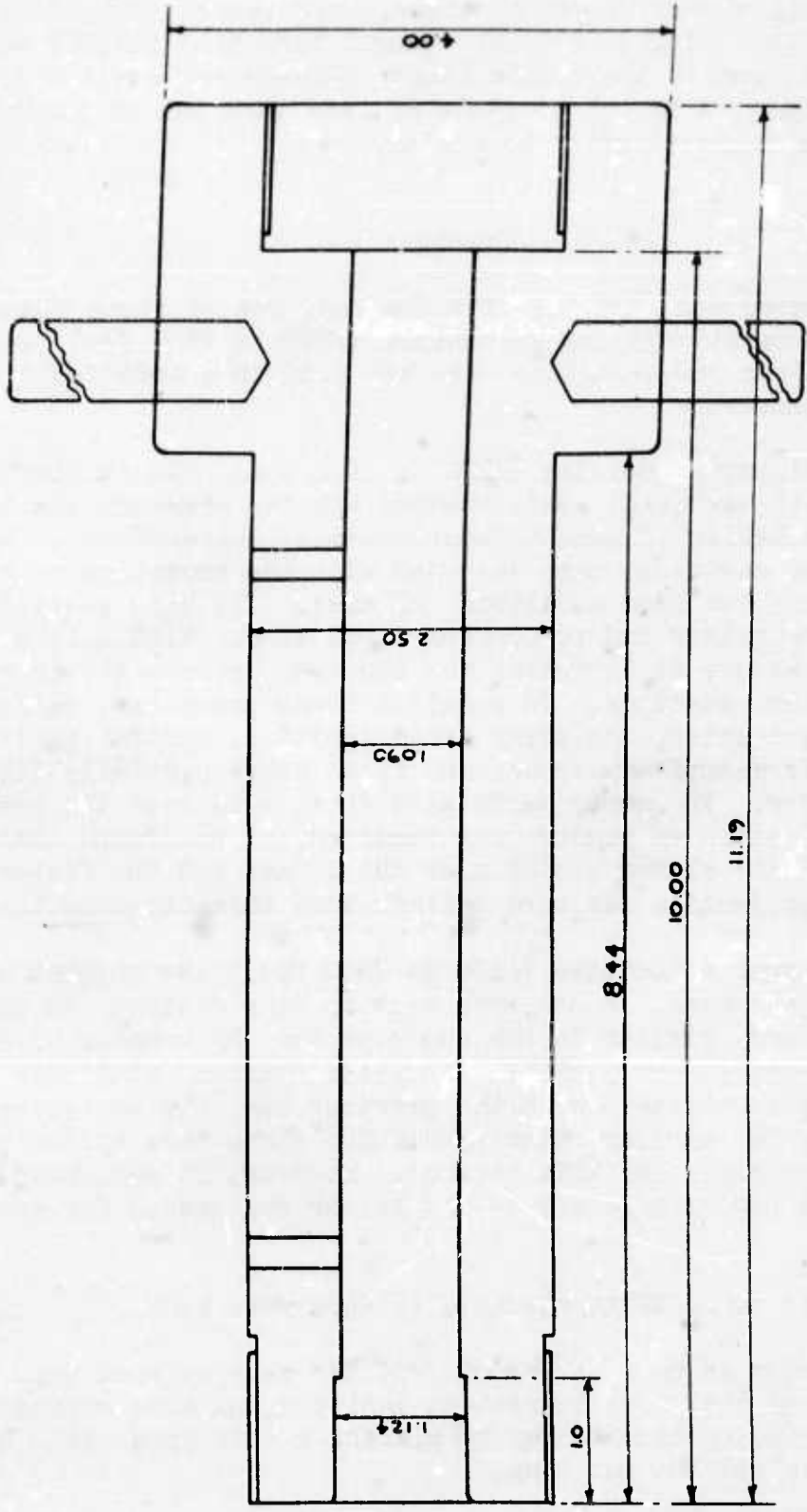few where piezoelectric gages were used.

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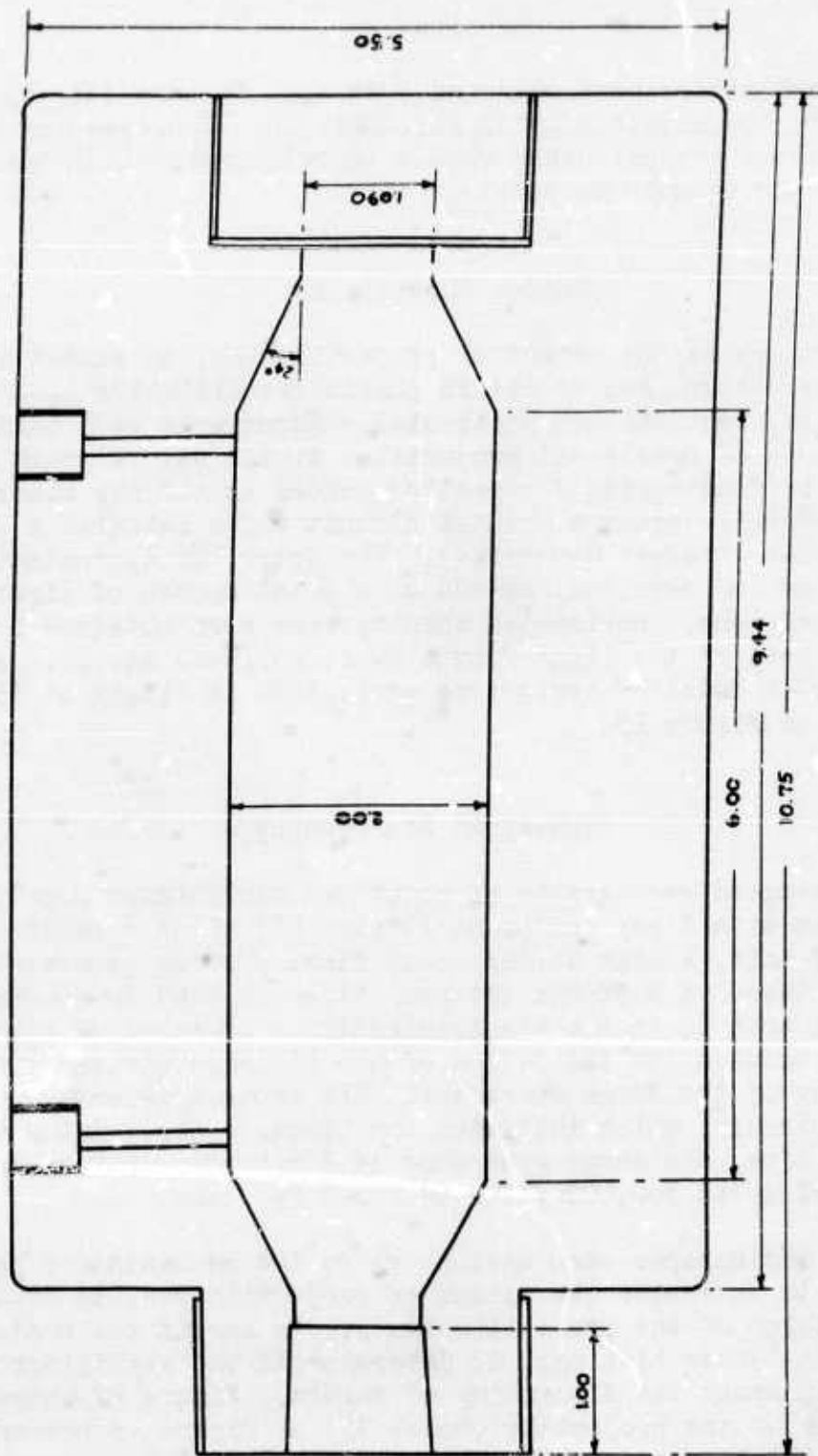Figure 13. Sketch of chamber for arrow-type projectile velocities
of 3200 to 5500 fps

Figure 14. Sketch of chamber for arrow-type projectile velocities of 4400 to 7000 fps

INSTRUMENTATION

Velocity

All velocities were measured over a 10-ft base line by means of 1- or 1.6-megacycle counter chronographs. The breaking of a printed silver circuit discharged a thyratron which, in turn, initiated the counter to start or stop.

Shadow Photography

To determine the extent of projectile yaw, to assist in projectile design, and to obtain possible qualitative aerodynamic information, vertical and horizontal shadowgraphs were taken simultaneously of nearly all projectiles in flight. A spark was obtained by discharging a capacitor across an air gap after the fired projectile broke a printed circuit which actuated a delay unit (Preset Interval Generator). The spark, of approximately one microsecond duration, served as a point source of light for the shadowgraphs. Horizontal shadowgraphs were obtained by reflecting part of the light from a front surfaced mirror. An example of a Model 39 arrow-type projectile in flight at 5565 fps is shown in Figure 15.

High-speed Radiography

High-speed radiographs of about one microsecond duration were taken with X-ray equipment (Figure 16) which consists of a control unit, a high voltage rectifier, a surge generator, and an X-ray tube. A micronex interval timer is used in conjunction with this unit to insert electronically, a preselected time interval between the initiation of the timing cycle and the triggering of the surge generator. The projectile breaks a printed circuit, which initiates the timing cycle. After the selected time, the surge generator is discharged, giving an impulse of up to 360,000 volts to the X-ray tube.

The radiographs were used to study the mechanism of penetration, to determine the extent of projectile yaw, to determine the condition of the projectile (e. g., to see if the projectile was intact before hitting), to determine if the stabilizer was on, and to study the discarding of sabots. Figure 17 shows a radiograph of the projectile (Model 35) of Figure 15 penetrating 1/2 inch thick armor at 60° obliquity, at 3185 fps.

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A
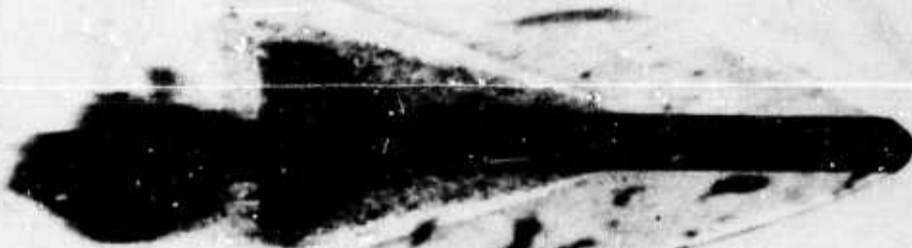
B

Figure 15. Shadowgraphs of arrow-type projectile (Model 39)
at 5565 fps

A - In vertical plane
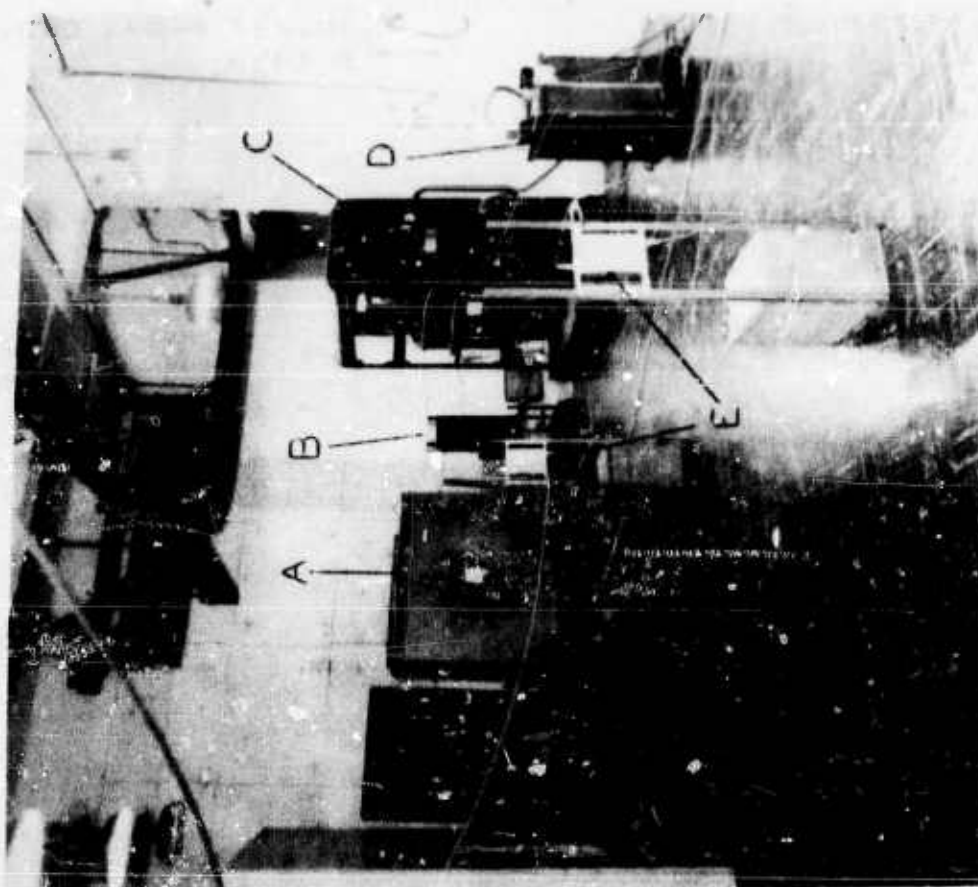B - In horizontal plane

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Figure 16B. X-ray range setup

A - Fragment protection box
B - X-ray tube (in oil)
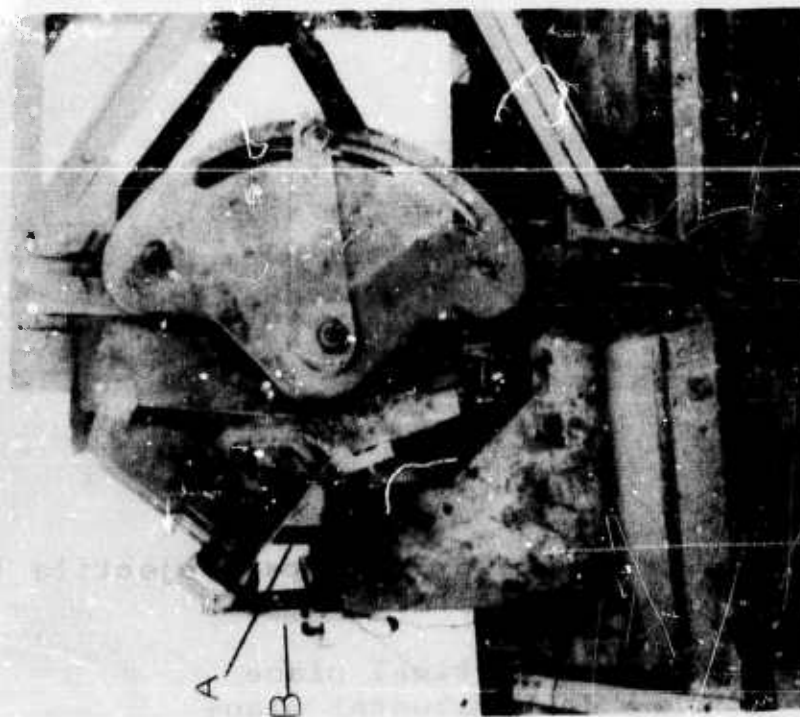C - Surge generator
D - Rectifier unit
E - Velocity screens

Figure 16A. Plate mount with fragment
protection box removed

A - Cassette
B - X-ray triggering screen
C - Plate

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Figure 17. Radiograph of arrow-type projectile (Model 35) penetrating 1/2 inch RH armor at 60° obliquity, at 3185 fps

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